Live 3D Imaging

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I have no conflicts of interest and I have no disclosures

Objectives:
- to understand the difference between 2D and 3D imaging
- to gain an understanding of the physics of 3D imaging
- to gain an understanding of the different modalities of live 3D, 3D zoom and full volume scanning

Introduction:

Echocardiography has contributed greatly to the understanding of cardiac structure and function. In over the past half century since the first cardiac images were obtained, the technology has advanced at whirlwind speed. While the concept of 3-dimensional (3D) has been around for over 30 years, it has been within the past 10 years, that advances in transducer design, electronic circuitry, piezoelectric crystals and computer chip speed that has led to the development of clinically usefully and affordable 3D systems. While first only possible on larger, bulky handheld transducers, recent advances have permitted the production and introduction into routine clinical practice of 3D TEE probes with live and reconstructive 3D capability. It is important to understand the differences between traditional 2D imaging and that permitted with 3D probes and within these the differences between 3D reconstruction from 2D scans, live 3D from matrix probes and finally stitched 3D volume sets. Live full volume (single beat) acquisition will also be introduced.

http://www.healthcare.philips.com
Review of 2D (planar scanning):

Image formation in 2D scanning is accomplished by assembling multiple scan lines across a small enough time frame to appear as a single image and then refreshing that image at a rate that makes it appear as if there is a continuous representation of cardiac structures. Each scan line is composed of pulses (packets or trains) of ultrasound waves emitted and received from discrete elements within the transducer. Each element is a piezo-electric crystal capable of both generating and receiving an ultrasound impulse. The variable – sequential stimulation of these individual elements within a transducer initiates phasic generation of sound impulses and by controlling the timing of the element- stimulation, the resultant wavelets can be focused, directed and steered. Most 2D (TEE) systems have 64-128 elements in a single row and may be called a 1D phase transducer. In this arrangement, the scan lines emerge along a single 2D plane and are limited to being steered along such a 2D plane.

http://belley.org  Ultrasound Transducers

Width of the scan line, separation of each scan line and sequential angle steering at typical line density 90 degree scan sector permit resolution along this left- right lateral or azimuth image plane of 0.8-1.1 mm. There is vertical divergence of the beam as it travels from the probe so there is some elevational (vertical) or 3 dimensional aspect to every 2D plane, usually <1 mm so this is largely ignored (but may account for certain artifacts: e.g. beam width). In contrast, resolution along the length of the beam or axial dimension is dictated by pulse length and repetition frequency and is much finer on the order of 0.2-0.3 mm.

http://e-echocardiography.com
3D Imaging Techniques with 2D transducers:

As early as the 1970s, attempts to assemble multiple planar scans into a reconstructed 3D model were performed. These included mechanical movement of the ultrasound transducer, either linearly or annularly. In each case, there were problems of size, motion artifact, extensive mechanical equipment and requirement of many cardiac cycles (with the assumption that nothing was changing!). The biggest advance came in the early 1990s with the development of 3D rotational reconstruction via an omniplane TEE probe. Utilizing the existing probe and rotational technology, hardware and software were developed to allow for sequential advancement of the multiplane array rotationally in either 3 or 5 degree increments. Timing with the ECG permitted assembly of these data sets to form a 3D rotational reconstruction of the heart. Off line analysis and dissection of this 3D data set could be performed and resolution was far superior to the methods previously described. These systems still are useful today. Limitations included the need for a TEE, difficulty in assuring that the probe was both stationary for primary studies and for repeat analysis, gated reconstruction thus subject to motion and temporal artifacts as well as a long delay in both data acquisition (e.g. 180° ÷ by either 7° or 5° at heart rates of ~ 60 or 1/sec = 25-36 seconds just for acquisition).

3D Transducer Development:

Later in the 1990s, advances in crystal fabrication permitted the assembly of multiple layers of piezo-crystal elements. If all elements of these initial systems were utilized in traditional beam-forming capacity, the power consumption, heat generation and circuitry required would be prohibitive. Initially, only portions of the matrix array was utilized in so called “sparse array” so that ~128 elements of the 2500 total were utilized at any one time and thus traditional 2D circuitry and beam formers could be used. To fully sample all of the array would require too many cables, generate too much heat and occupy too much size.
Breakthroughs in crystal technology allowed the “growing” of pure crystals in homogeneous solid-state domains and piezoelectric qualities. Part of the pre-beamforming circuitry was moved directly to the transducers – handles, the remaining 128-256 beamforming occurring within the ultrasound system itself. These advances combined to decrease the size, energy consumption (and thus heat) as well as circuitry required. Further miniaturization of boards to ASIC (application specific integrated circuits) allowed these components to be fitted into transducers. The combined product of these advances is the 3D matrix probe at the heart of current 3D echocardiographic imaging.

3D Imaging modalities:

Just as it is fundamentally impossible (due to excessive side lobes, clutter and interference) to generate a planar 2D scan all at once so rather each scan plane is the assembly of multiple scan lines separated in time, generation of 3D images are similarly limited but now in both lateral (azimuthal) and vertical (elevation) dimensions. Hence 3D volume imaging occurs through the compilation of multiple 2D imaging planes (although data from these may be assemble coincidently--- more to follow). As previously described, this had been done through mechanical movement of the transducer or through axial movement of the array as with rotational TEE 3D reconstruction over multiple sequential cardiac cycles.

As a reminder, to generate a 2D scan, sequential beams are generated in a phased pattern across the linearly arranged elements of the transducer. For x plane imaging this is performed in two orthogonal planes but follows a similar sequential pattern in each 2D scan as if there were two discrete perpendicularly aligned linear arrays. 3D matrix scanning permits sampling of a whole matrix of scan lines in a cubed arrangement. Much like an older cathode ray tube would “rasterize” across the screen and produce the display we know as television, the matrix transducer sends out and analyzes sequential beam (lines) across the whole 3D sector.

Unlike 2D phased array transducers, 3D matrix transducers permit sequential scanning of a series of 2D slices displaced over a series of elevation angles. Also different from mechanical or electronic reconstructions of the elevation 2D slices which are acquired in sequential heart beats, the 3D matrix probe permits these scan planes to be acquired many times per second and hence the full volume is acquired with a single heart beat and in fact many times per cycle. Thus the term “live-3D” imaging is used as the pyramidal wedge shaped data set or “frustrum” is completed within a sufficiently short period of time that it appears to be “live” in the same way that motion pictures, although single static frames but displayed at > 24 frames per second appear to have live, real-time motion to our eyes.

(NB: it is called a frustrum not a pyramid as the base is curved).
Several additional scanning techniques are utilized. It is possible to analyze or receive a greater number of beams (lines) than one transmits. It is like using a single flash bulb to light up a scene but then discrete receptors in your camera to capture the illuminated image. Typically there are four received lines for each transmit, each split 1° laterally and elevationally. This permits sampling over a much greater volume for each transmit line and thus shortening the total sampling time and gaining in frame rate. Scan line density (the distance between each imaging beam) is also varied. They can range from the 1 x 1° above to 2.0 x 2.0° for 3D mode.

The subsequent challenge is how to display this 3D volume data set. It may be displayed as any of the single 2D slices from which it is comprised, (slice rendering). In this fashion, the 3D volume set not only permits display of traditional scan planes obtained via axial transducer rotation and probe manipulation of the planar 2D scan plane, but by cutting the virtual data set in any desired plane, multiplane reconstruction (MPR) can be achieved. The most easily understood example is the orthogonal plane or C-mode.

A second way of displaying the data is through 3D depth perception. Visual displays can manipulate opacity and color depth coding and permit the perception of depth. Finally, the data can be presented as a 2D slice of the 3D data volume set (sort of slice rendering plus the 3D reference cut. Finally, the systems allow simultaneous display of multiple 2D scan planes acquired simultaneously.
3D Volume Set Displays: Live 3D, single beat-full volume, 3D zoom, gated-stitched full volume:

Live or real time 3D makes use of the whole sampling set of the matrix transducer. Typically this is a 60° x 20° degree volume set for TEE. This is also termed live 3D narrow angle or real-time 3D. By using only 20° of elevation, frame rates can be preserved (~ 20-30 Hz). Full volume 3D utilizes the full volume capacity of the matrix array. In this case the frustrum is 60° x 60° - 90° x 90° and anywhere from 4-16 cms or so in depth typically. It takes a long time to sample each scan plane and thus sacrifices must be made. Typically line density is reduced and frame rates approach 5-6 Hz. Images will appear not appear smooth at this low refresh-frame rate. A modality unique to matrix probes is 3D zoom. Also a live or instantaneous scan mode, in this case the complete volume set is reduced to a subset of the total frustrum anywhere from 20° x 20° to 90° x90° and of various elevations determined by the user-selection. In this way large lateral volumes can be imaged but frame rates are similarly low (5-6 Hz). A final modality is gated-stitched for gated full-volume reconstruction. This makes use of the acquisition of multiple lower elevation volumes (either 4 or 7 depending upon user selection) and assembly of their volume data together or “stitched” by timing the points with the ECG. Selecting an increased slice number gains frame rate as the volume sampled each time is smaller, but requires a longer time in which no motion of the probe or heart is allowed.

<table>
<thead>
<tr>
<th>Scanning Mode</th>
<th>Live 3D (narrow angle)</th>
<th>Single Beat Full Volume</th>
<th>3D zoom</th>
<th>Gated Full Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>60 x 30</td>
<td>90 x 90</td>
<td>20 x 20-90 x 90</td>
<td>90 x 90</td>
</tr>
<tr>
<td>Frame Rate</td>
<td>20-30 Hz</td>
<td>5-6 Hz</td>
<td>5-10 Hz</td>
<td>20-40 Hz (4 beat)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>40-50 Hz (7 beat)</td>
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<td>Temporal Resolution</td>
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<td>Mod-high</td>
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<tr>
<td>Spatial Resolution</td>
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<td>Lowest</td>
<td>Highest</td>
<td>Low</td>
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<tr>
<td>Color Flow Doppler</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Modified from Mahmood et al Anes Analg 2012;115:779-84

In this stitched modality, both superimposition of the ECG tracing as well as examination of the volume set in the full view mode permits detection of irregular timing of events or stitched artifacts. These will show up as irregularities in the lateral view of the assembled data-set volume and occur because of dys-synchrony between the events
either due to irregularities in the heartbeat and therefore sample interval or prove-heart motion.

Multi-pane display and C plane:

Two modalities unique to 3D volume set displays and rendering are the capacity to display multiple planes and 3D data-set cutaway views simultaneously and the reconstruction of a non-echo plane or C-plane from the 3D data set. In the first instance, the display can be configured to display the 3D frustrum with a cut away view, but also display the conventional 2-D planes (typically horizontal and vertical – or some other orthogonal combination) at the same time. This permits the more rapid understanding of where a particular 2D plane is slicing the heart and can allow optimization of the more rapid 2D imaging modality. In the second instance, a planar cut and display can be performed off line and reconstructed through any plane of the 3D volume set. This permits views that are commonly not obtained through conventional windows of 2D TEE. For instance, serial C plane display can be developed for sequential short axis slices of the left ventricle in cross section from a 3D data set imaged and generated from a full volume set with a window in the middle esophagus and similar to a four and 2 chamber rotational 3D data set.
References:


Mahmoo, Warraich, Shahul, Qazi et al. En face view of the mitral valve: Definition and acquisition. Anesth Analg 2012;115: 779-84

NB: I would also like to acknowledge the contributions of Dave Prater (Philips) to the accuracy and production of this handout.